Damage Simulations in Hard and Deeply Buried Targets Due to Blast and Shock Loading

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Abstract

The counter-proliferation of Weapons of Mass Destruction (WMD) continues to remain one of our nations highest defense priorities. The defeat of systems within hard and deeply buried targets (HDBT), namely tunnels, presents the greatest challenge. When a weapon detonates in a confined area, the airblast effects are much more severe than those from a free air detonation. Current semi-empirical models for predicting airblast are limited with regard to tunnel geometry and weapon location, and predictions of internal damage to structural components and equipment are based on very limited experimental data. The size and complexity of numerical models required to assess functional damage to a facility require very high performance computing resources. This paper outlines recent attempts to simulate airblast and equipment response to blast loads in confined environments using scalable software on the ERDC MSRC parallel computers.

Background

The geometries of hard and deeply buried targets in rock range from long straight tunnels to various types of intersections, expansions, constrictions, chambers, rooms, alcoves and multiple levels. Because of the many complex configurations, field-testing all of the various configurations is impractical. Semi-empirical methods are very limited, and in most cases, inadequate for developing methods for damage assessment. Substantial high-performance computing resources are required for an accurate numerical model representation of the complex three-dimensional geometry and functional layout, the interaction of the blast wave with mission-critical and support equipment and the response of the equipment to failure. Three approaches have been taken to validate numerical modeling techniques. Small-scale experiments have been conducted to investigate airblast in complex tunnel geometries. Equipment response and failure modes have been investigated in full-scale tests with idealized stand-alone equipment, and in full-scale tests with interconnected functional systems. This paper describes one approach, in which the full-scale geometry is approximated in two- and three-dimensions and the airblast environment is decoupled from the loading and response of an idealized, stand-alone component that represents the equipment and its attachment details. Of the components tested in a full-scale facility, a generic tank was chosen as the example for this simulation.

Objective

The overall objective of this research was to develop and validate HPC methods for assessing functional damage to HDBT from internal detonations. The objectives of the Challenge Project for the year 2000 are: (a) to conduct a series of numerical simulations to determine the effects of tunnel geometry on airblast overpressure and dynamic pressures propagation, and (b) to assist in field test planning by quantifying equipment response to in-tunnel blast environments.

Computer Codes used in Numerical Modeling

Blast environments were simulated using two scalable hydrodynamic codes, CTH and SHAMRC. The equipment response was simulated with a parallel version of DYNA (ParaDyn), a finite element code. The calculations were conducted on the Cray T3E, IBM SP, and SGI Origin 2000 at the U.S. Army Engineer Research and Development Center (ERDC), Major Shared Resource Center (MSRC). The calculations involve modeling high explosive initiation and detonation effects, large deformations, and damage. The problems are also three-dimensional and involve complex interactions with objects in the blast flow. CTH [1], SHAMRC [2], and ParaDyn [3] are multidimensional scalable computer codes widely used in the defense research and development community to model shock physics and large deformation problems. CTH and SHAMRC are finite volume-based, explicit time integration methods and use Eulerian formulations. ParaDyn is a rate-based, finite-element, explicit time integration method and uses Lagrangian formulations.

The Lagrangian form of the conservation equations leads to a computational grid that deforms with the material, whereas the Eulerian computational grid is fixed. The numerical algorithms used in solving the conservation equations (mass, momentum, energy) are derived using either finite element or finite difference methods, along with constitutive relations and failure models. The solution is advanced in time using an explicit time integration scheme which requires very small time steps to maintain stability. Since these applications consist of very short transients, very small time steps are required to capture the physical phenomena. In order to obtain the required spatial resolution and conditionally stable time integration, these codes are computationally intensive and require large memory, enormous computing time, and storage space for I/O operations.

Airblast Simulation

Ideally, the entire calculation--from the initiation of a charge, blast propagation, interaction of the blast wave with the equipment, and equipment response--should be conducted in three dimensions as a single, coupled calculation. Limits to computational resources require that we make approximations to the geometry in order to reduce the calculation size. Since the environment calculation must be decoupled from the loading and equipment response, only limited aspects of the problem can be simulated in a detailed three-dimensional grid. For the tunnel geometry in Figure 1, the differences in problem size and the computational resources required for these two approaches are given in Table 1. If the tunnel geometry is represented as a planar two-dimensional structure, the localized charge has to be distributed so that the mass of the distributed charge equals the mass of the concentrated charge (Figure 2). The results of these two-dimensional calculations are compared to experimental data from full-scale tests in Figures 3 and 4. The two-dimensional calculation for this tunnel is compared to a three dimensional calculation in Figure 5. The three-dimensional calculation waveforms are compared to experimental data in Figure 6. Figures 7 and 8 show the blast wave propagation down the tunnel before and after engulfment of the tank. The reflected shock from the back wall and the multiple shock reflections from the alcove are evident in the waveforms.

Equipment Loading and Response

In these calculations, the tank is modeled as a solid steel structure. Since we assume that the tank is a solid, rigid structure, any modification of the load on the structure, that would result from interaction of the airblast with an actual, deforming structure is lost. However, these losses are considered small, as the tank orientation does not change significantly during engulfment. Figure 9 shows the airblast load calculated on the front face of a tank structure using a two-dimensional approximation and compared with experimental data. Figure 10 illustrates the load calculated at four points around the tank. Figure 11 shows results on the front face of the tank from a three-dimensional calculation compared with experimental data. The distribution of the load at four points around the tank and at mid-height of the tank are shown in Figure 12. Since the tank was located just upstream of the alcove, the multiple reflections from the back wall of the alcove have a significant effect on the loading and response of the tank. The loads calculated on the two-dimensional and three-dimensional solid structure are applied to a three-dimensional finite element representation of the tank, and comparisons of test results with calculations for the tank response are shown in Figure 13.

Discussion of Results

Clearly, the results of the calculations and comparison with tests of idealized equipment components included in a full scale experiment show that the two-dimensional representation of the tunnel geometry and the airblast calculation using this representation produces significant differences with test data. The load calculated at one cross-section on the equipment is a reasonable approximation as long as the equipment geometry cross-section does not vary in the vertical direction. The uniform cross-section lends itself, not only to a simplified representation of the load, but also to an accurate three-dimensional model of the equipment. It appears that the discrepancy between the two-dimensional numerical simulation and the experiment are the result of the planar approximation in which a concentrated charge is simulated with one that is distributed across the cross-section of the tunnel. The three-dimensional calculation of the detonation and airblast propagation reproduced the shock arrival and the incident shock strength quite accurately. The arrival of the reflections in the calculation are not consistent with the data and are the result of the reflection from the back wall and multiple shock interaction from the storage chamber and the alcove adjacent to the tank structure and the airblast gage location at Station 48. The response of the tank was over-predicted, but at this level of response, small variations in the load can lead to large increases in response. Overall, it appears that the two-dimensional planar approximations lead to unacceptable results and problems of this type will have to be addressed by three-dimensional calculations. Even with the large computing resources that would be required, it is much more cost effective to use three-dimensional numerical models than to conduct full-scale tests. At this time, the most feasible approach for assessing functional damage in hard and deeply buried facilities lies in the judicious use of engineering models, small-scale experiments, full-scale tests and HPC simulations. And in the near future, we need to validate coupled Eulearian/Lagrangian codes against this class of problems.

Acknowledgements

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3. Crepau, J., “SHAMRC: Second-Order Hydrodynamic Automatic Mesh Refinement Code,” Vol. 2: User’s Manual, Applied Research Associates, Inc., Albuquerque, NM, 1998.

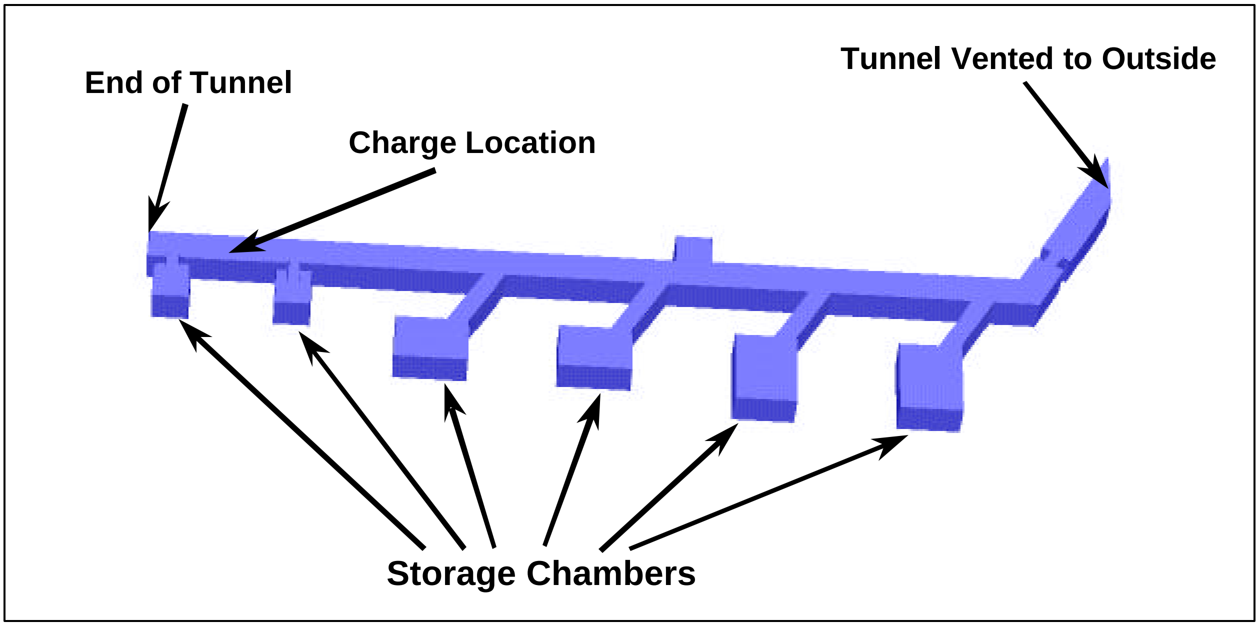


Figure 1. Full-scale tunnel layout.

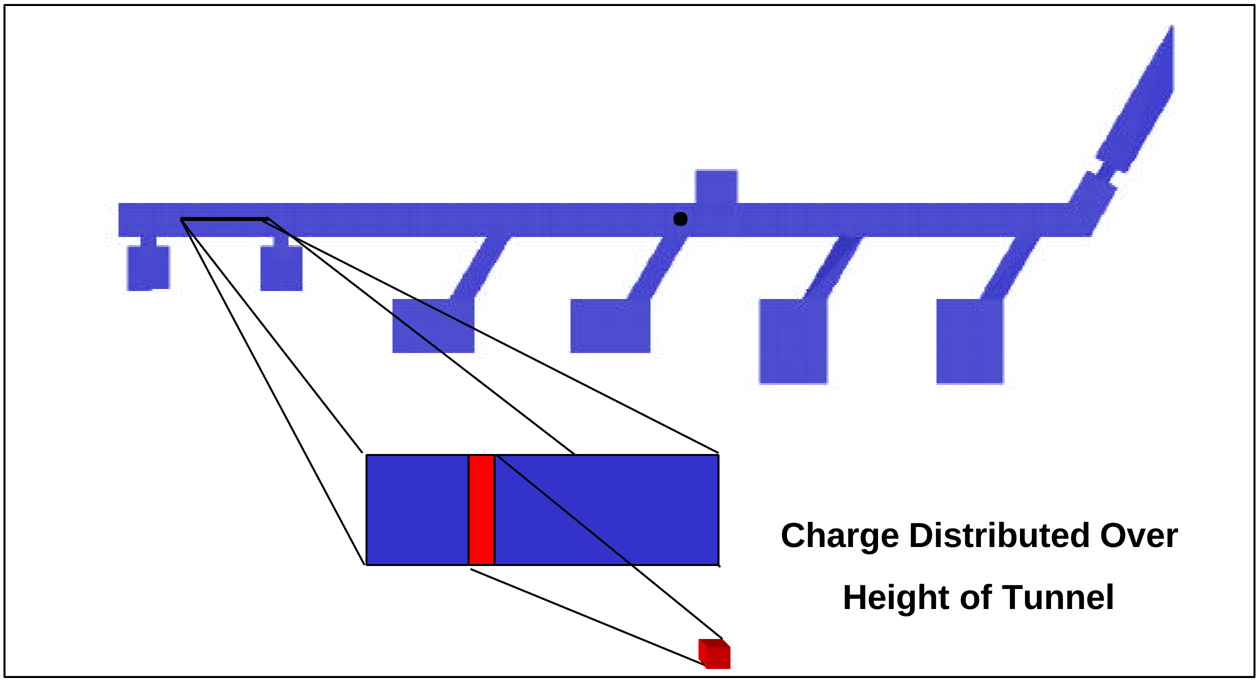


Figure 2. Two-dimensional planar model of tunnel.

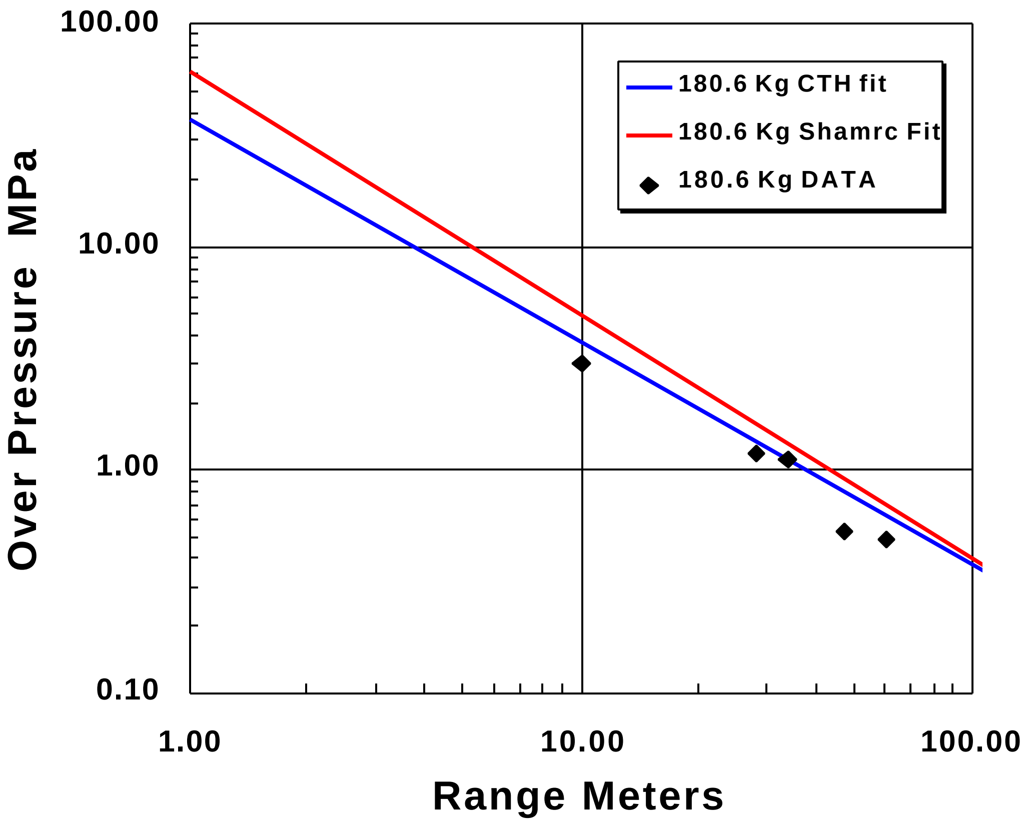


Figure 3. Comparison of pressure vs range from 2-D model with test results.

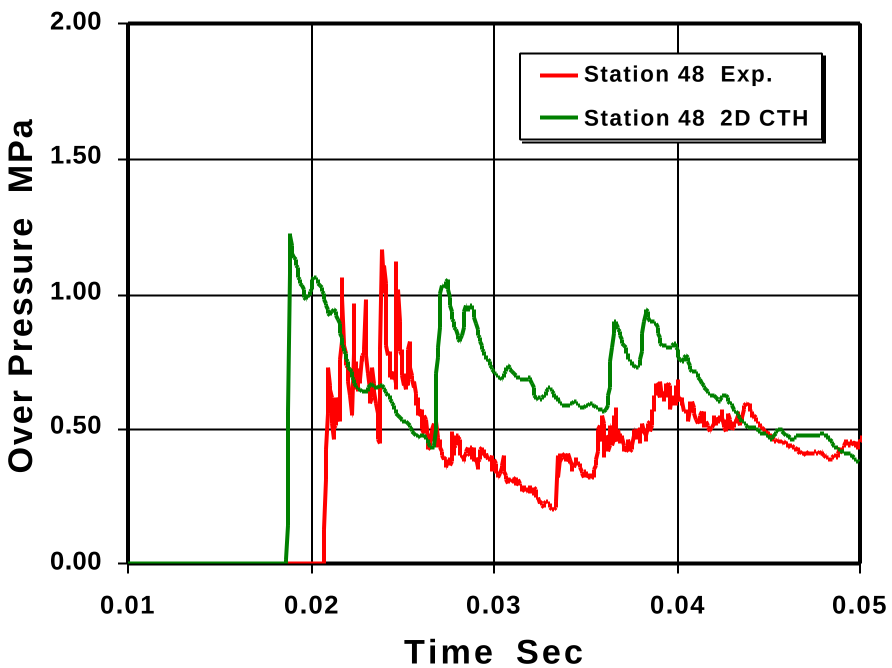


Figure 4. Comparison of pressure history from 2-D model with test results.

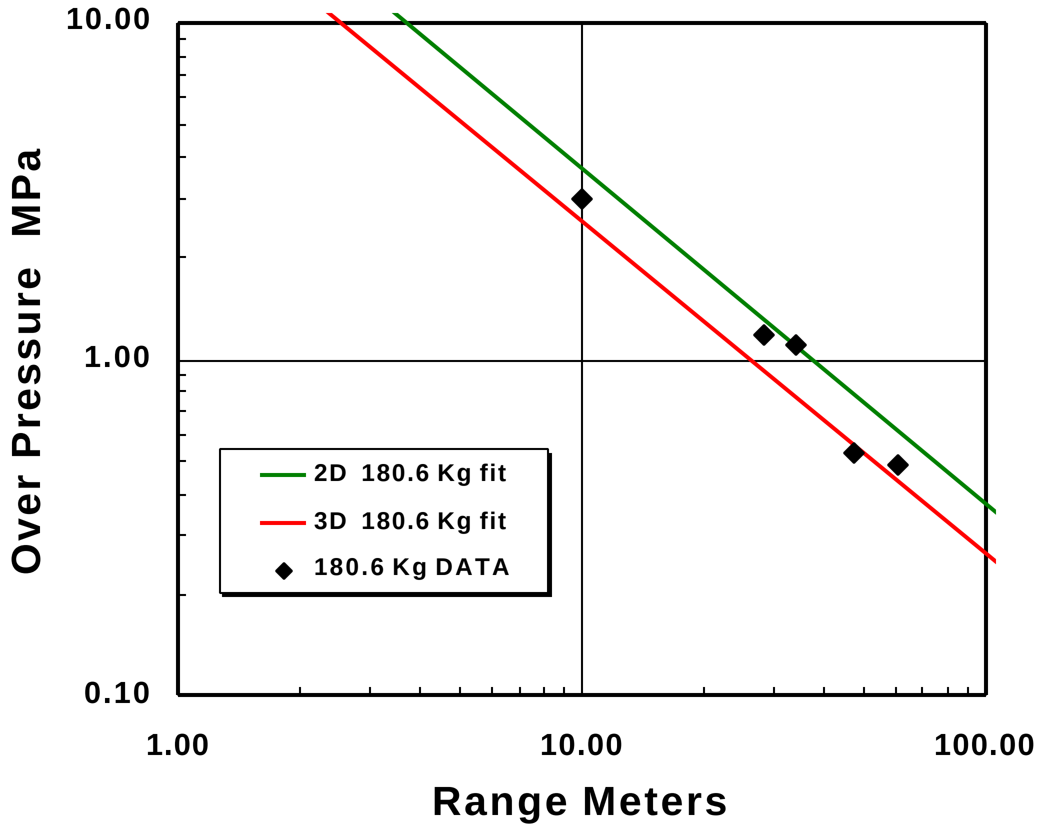


Figure 5. Comparison pressure vs range from CTH 2-D and 3-D calculations.

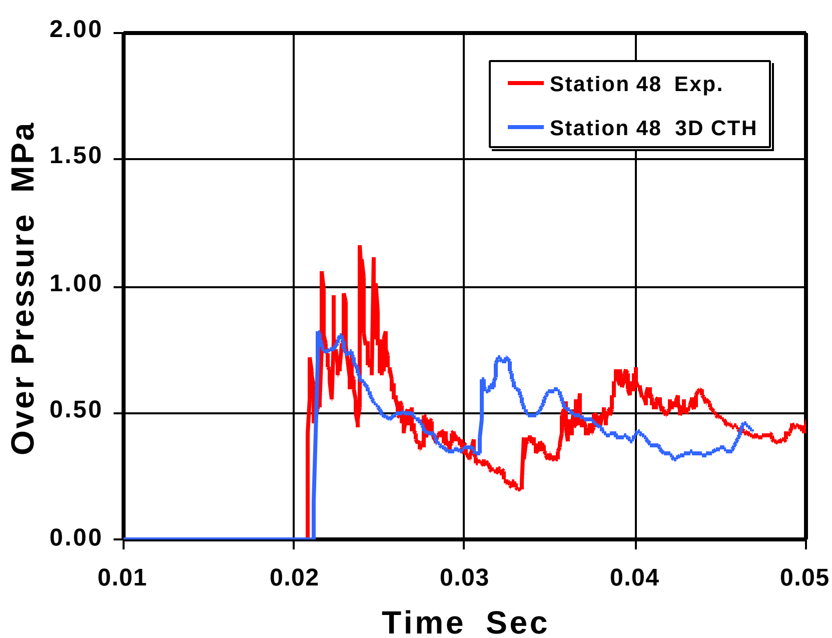


Figure 6. Comparison of pressure history from 3-D model with test results.

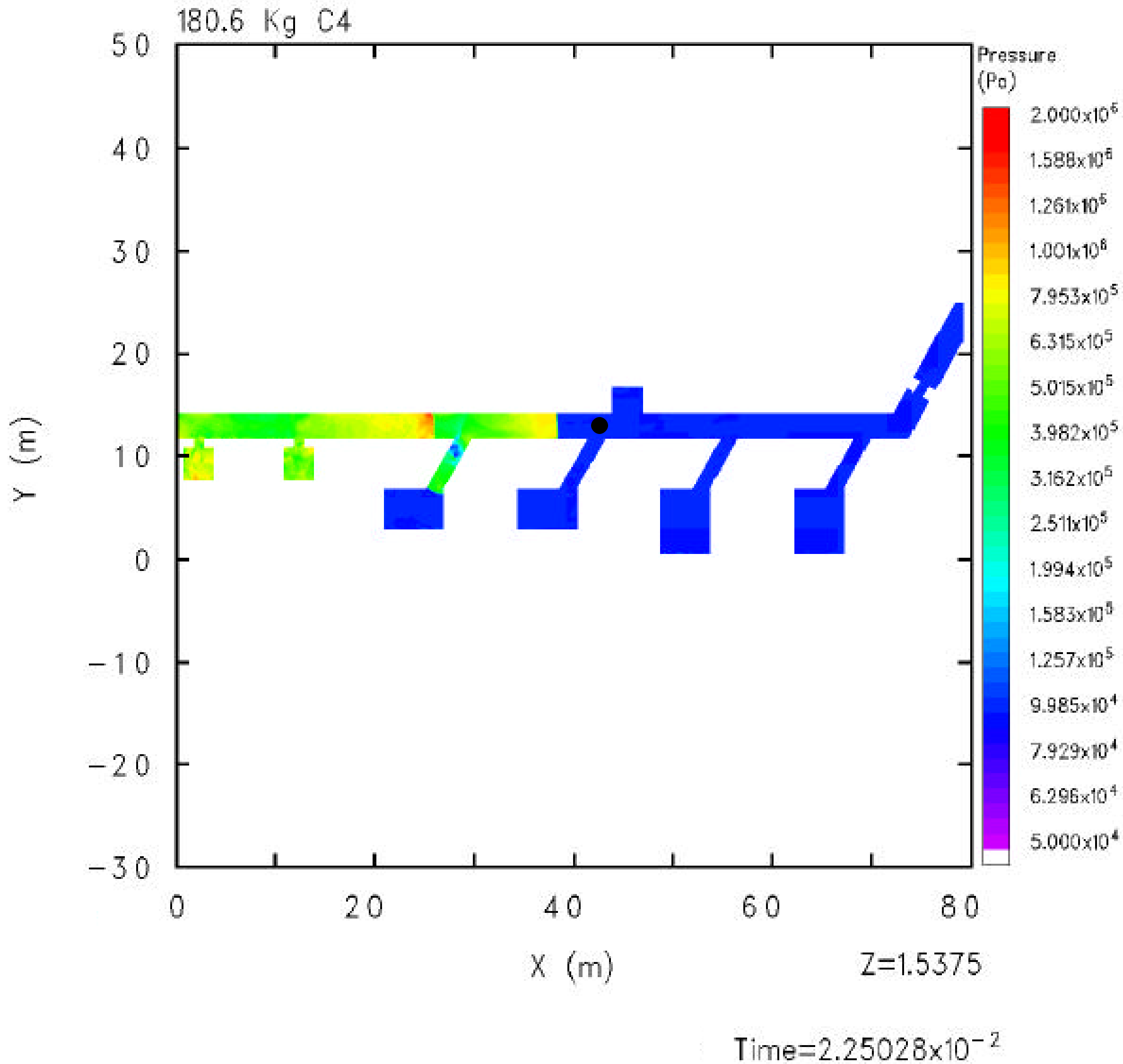


Figure 7. Blast wave propagation from 3-D calculations in tunnel before engulfment of tank.

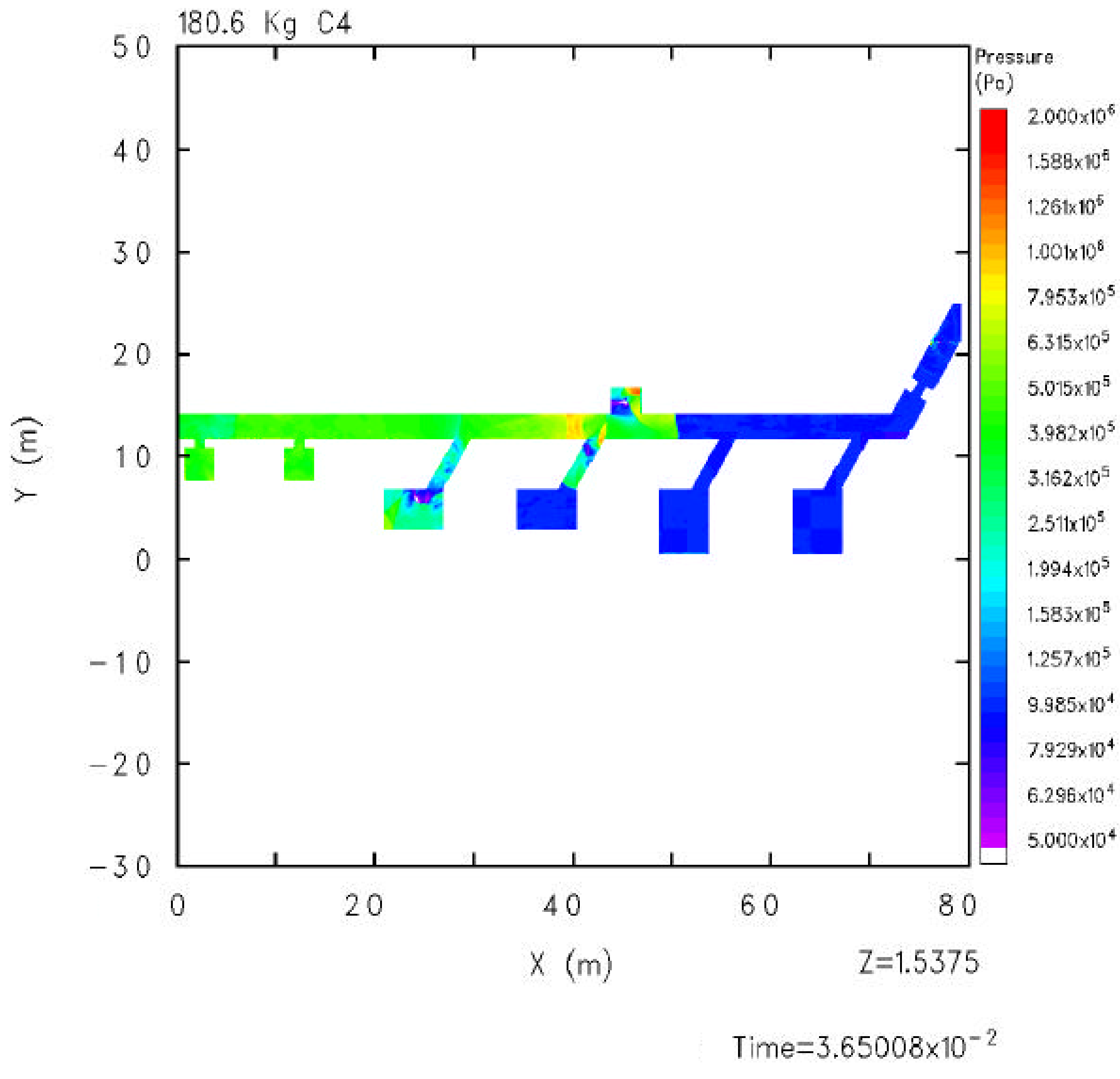


Figure 8. **Blast wave propagation from 3-D calculations in tunnel after engulfment of tank.**

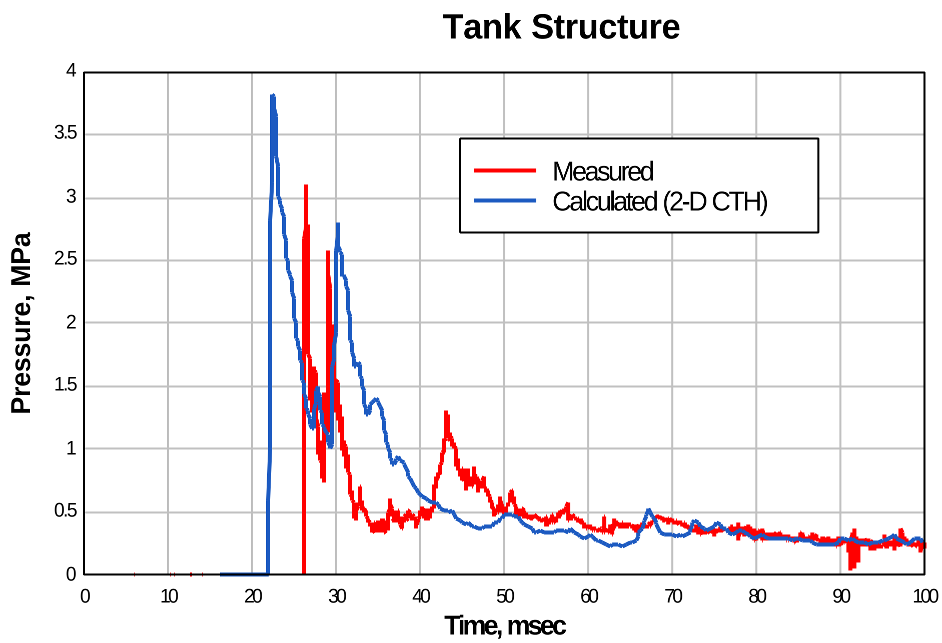


Figure 9. Comparison of load on front face of tank from 2-D calculation with test data.

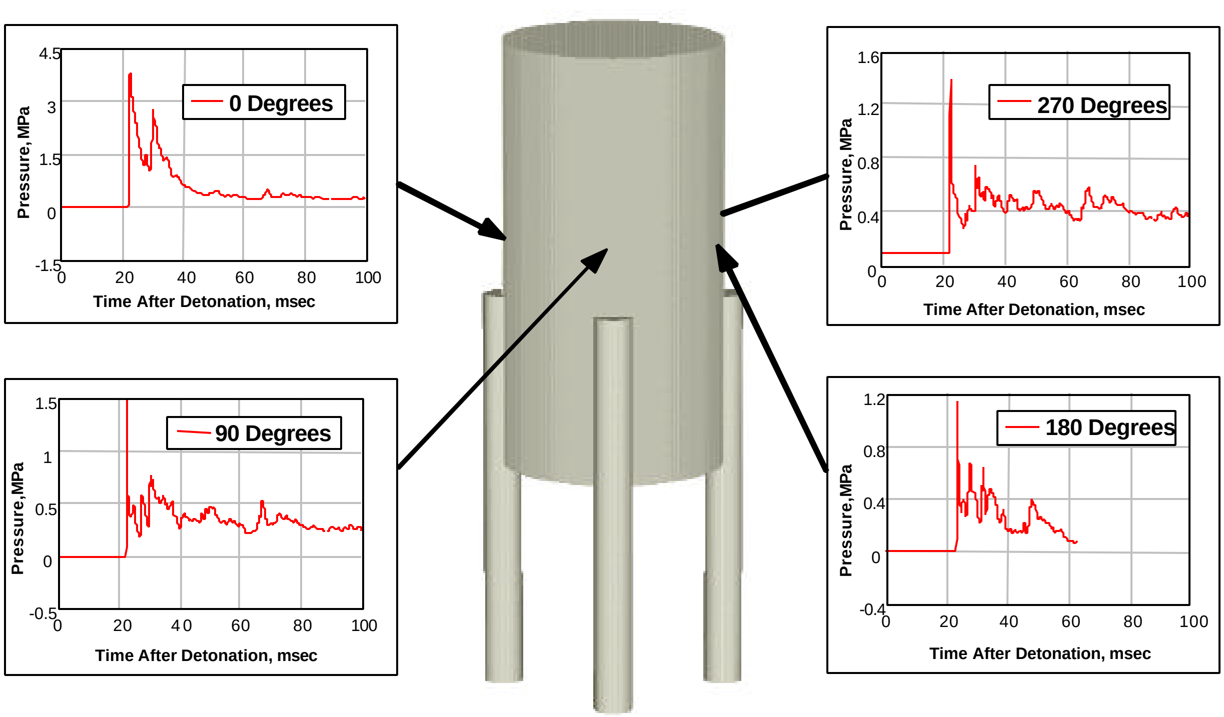


Figure 10. Distribution of load on tank from 2-D calculation.

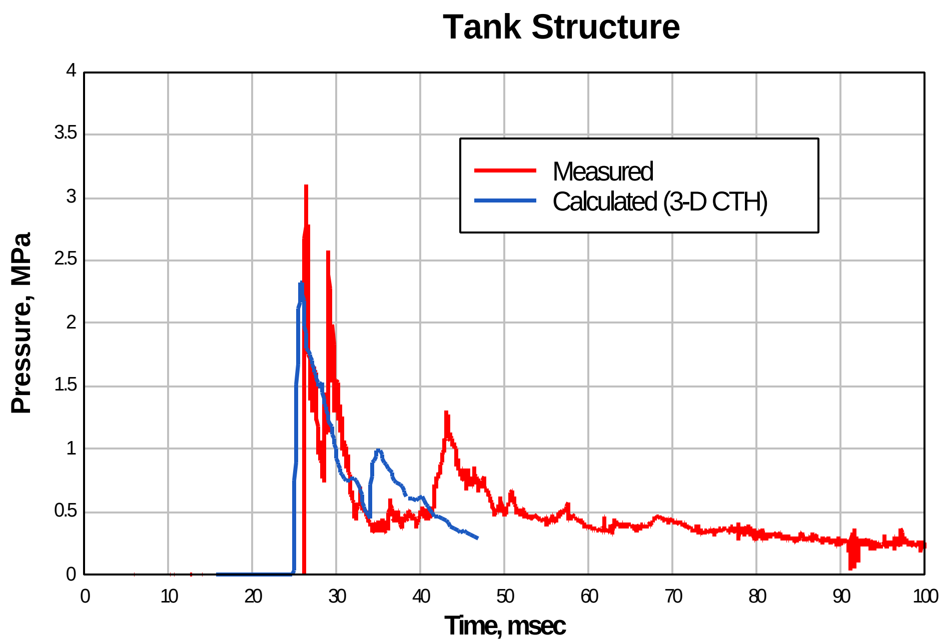


Figure 11. Comparison of load on front face of tank from 2-D calculation with test data.

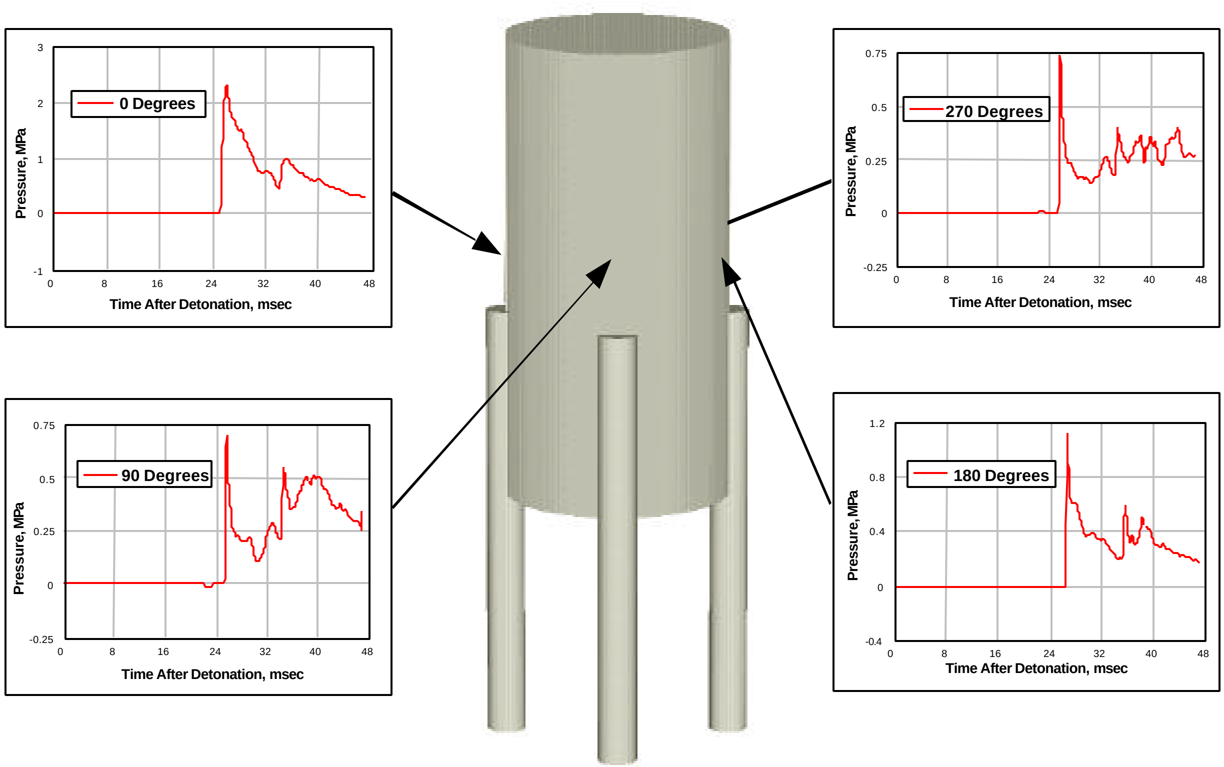
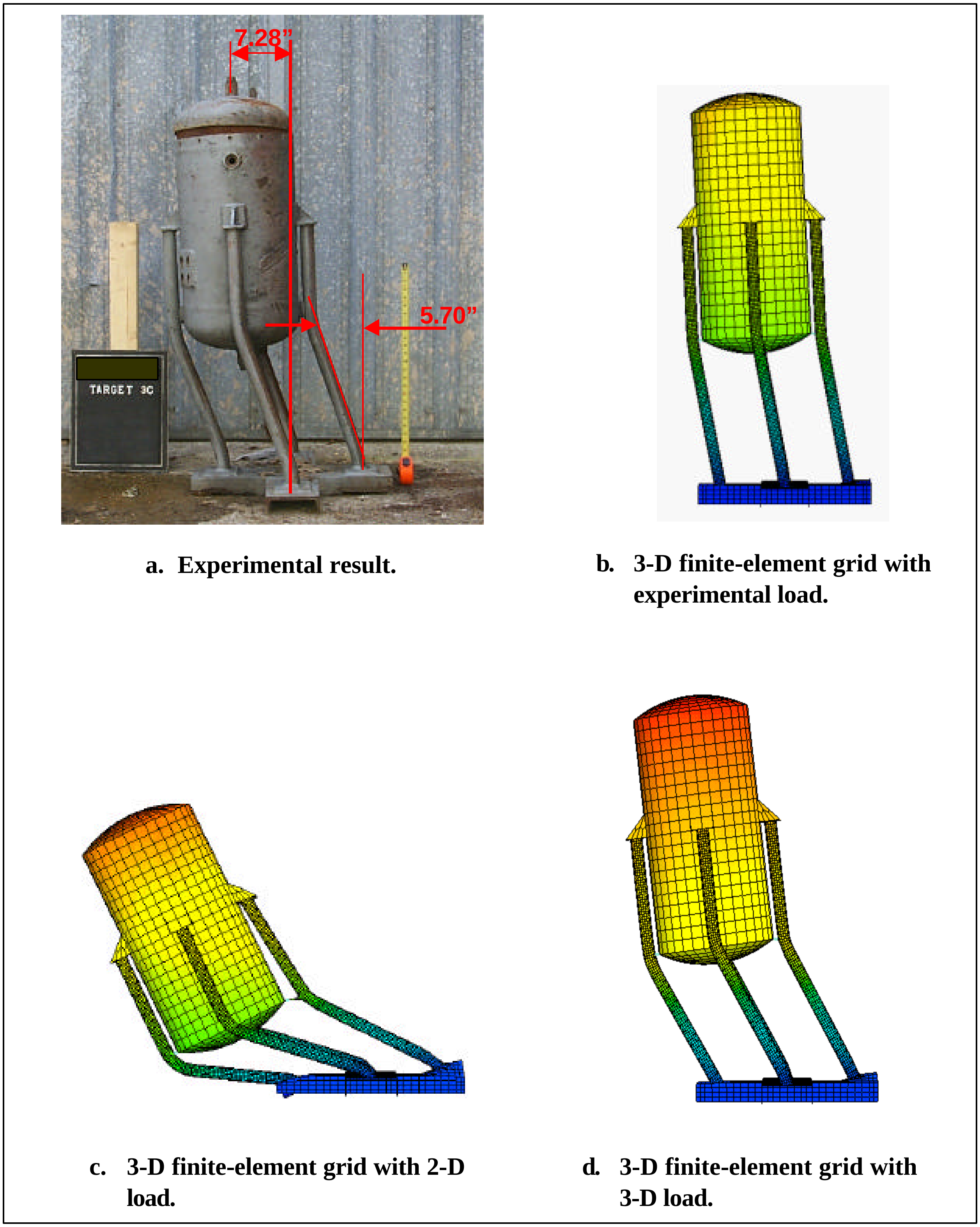


Figure 12. Distribution of load on tank from 3-D calculation.



a. Experimental result.

b. 3-D finite-element grid with experimental load.

c. 3-D finite-element grid with 2-D load.

d. 3-D finite-element grid with 3-D load.

Figure 13. Calculated (with loads from CTH) and experimental response of tank.

Table 1. Comparison of computational resources for 2-D and 3-D tunnel airblast calculations.

	2-D Calculation	3-D Calculation
Machine	IBM-SP	T3E
Processors	96	256
Code	Parallel CTH	Parallel CTH
Grid Size	0.8 million cells	33 million cells
Minimum Cell Size	50.0 mm	60.0 mm
Width of Grid	80 meters	80 meters
Height of Grid	25 meters	25 meters
Memory Size	6.5 Mbytes	12 Gbytes
Average File Dump Size	160 Mbytes	65 Gbytes
Run Time	1,000 cpu hours	25,000 cpu hours